

**REMOVING ACTIVITY-RELATED RADIAL VELOCITY NOISE TO
IMPROVE EXTRASOLAR PLANET SEARCHES**

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We have made significant progress towards the proposal goals of understanding the causes and effects of magnetic activity-induced radial velocity (v_r) jitter and developing methods for correcting it. In the process, we have also made some significant discoveries in the fields of planet-induced stellar activity, planet detection methods, M dwarf convection, starspot properties, and magnetic dynamo cycles.

We have obtained super high resolution ($R \sim 200,000$), high S/N (>300) echelle study of joint line bisector and radial velocity variations using the McDonald 2-D coude. A long observing run in October 2002 in particular was quite successful (8 clear nights). We now have close to three years of data, which begins to sample a good fraction of the magnetic cycle timescales for some of our targets (e.g., kappa Ceti; $P_{\text{cyc}} = 5.6$ yrs). This will be very helpful in unraveling the complex relationships between plage and radial velocity (v_r) changes which we have uncovered (see below). Preliminary analysis (Saar et al. 2003) of the data in hand, reveals correlations between median line bisector displacement and v_r . The correlation appears to be specific to the particular star being considered, probably since it is a function of both spectral type and rotation rate. Further analysis and interpretation will be in the context of evolving plage models (see below) and is in progress. This work has been in collaboration with Univ. of Texas, Austin PhD thesis student Diane Paulson, and Univ. of Heidelberg PhD thesis student Sebastian Els.

Work continues on reanalysis of a longer time series of Lick data on velocity "jitter" (σ_{vr}) data (to look for relations between jitter and other stellar properties), and also revisiting using activity- v_r correlations to correct for the jitter. Initial results were presented in Saar et al. (2003). We find that the Hyades data agrees well with the trends seen in the Lick data, and emphasize the σ_{vr} minimum in mid-to-late K stars (Paulson et al. 2002). Thus, even relatively active stars in this spectral range are still good targets for planet searches. We find that simple ways of correcting v_r noise using activity fluxes (e.g., Saar & Fischer 2000) will likely be ineffective on stars where short-term (rotational) activity amplitudes dominate over long-term (magnetic cycle) variation (Paulson et al. 2002). Still, the improved analysis increases the average v_r correction possible by this method (from 45% to 57% of the total non-random noise). The fraction of successfully corrected stars drops somewhat though, from 29% to 22% of the Lick planet survey sample; these include mostly lower activity stars with strong cycle signals.

We have begun detailed semi-empirical modeling of the effects of plage on v_r noise in rotating G stars using solar line bisectors at various disk positions and plage intensities as proxies for stellar bisectors. We find a somewhat different rotational phase dependence for the v_r perturbation than predicted previously using simpler models (Saar et al. 2001), but the amplitudes are still large enough in active stars to be troublesome (as much as 60 m/s in the worst cases for $v \sin i > 5$ km/s). Initial results were presented in Saar (2003); a detailed paper with a more extensive suite of models is also in preparation (Saar 2004).

One result of this plage modeling is the realization that correcting for plage will be more difficult than correcting for spots. This is because plage alter the local convective velocity structure in an observable way, unlike spots (which alter the thermal structure, but in so doing are so dark that their convective velocity effects are largely hidden from

view). Combining this with the fact that plage areas are typically much larger than corresponding spot areas implies that it will be very important to devise methods for correcting for activity perturbations from plage. One major focus of our research in the upcoming year will be to develop methods to correct for plage effects on radial velocities, perhaps using line bisector fluctuations. Several of our McDonald echelle targets have significant plage coverage, and thus will be excellent test cases for plage correction methods.

Some work growing out of the spot and plage models has been explanation of the short period velocity fluctuations in some Hyades stars by a combination of spots and plage. Comparison of σ_{vr} for Hyades stars with relations between σ_{vr} and rotation and activity for field stars (Saar et al. 1998) are in good agreement (Paulson et al. 2002; Saar et al. 2003). This suggests that the same activity mechanisms generating additional v_r jitter seen in the Lick database for field stars are also operating in the Hyades. We have also been able to approximately model the much of the rotational v_r variation of one Hyades star with a combination of spots and plage, using the plage models described above (Paulson et al. 2004).

We have applied what we have learned from the plage models to observations of v_r variations in the M dwarf GJ 699 (Barnard's star, M5V). Kurster et al. (2003), among other things, find increased H alpha emission correlated with increasing blueshift. We interpret as possible evidence for a net convective redshift in the quiet spectrum of M dwarfs (in contrast to the net blueshift in the Sun and FGK stars). This net redshift is then reduced in magnetic plage to produce the observed correlation.

In a new development, we have been exploring use of linear polarization as a diagnostic for the properties of exoplanet atmospheres (Saar & Seager 2003). The idea makes use of the fact that most late-type stars generate extremely little linear polarization ($\sim 0.02\%$), while starlight reflected off the exoplanet will show significant polarization ($\sim 10\%$). Thus, for a penalty of a factor of 10 in initial detectability, study of exoplanets in linear polarization enhances *contrast* between planet and parent star by a factor of 1000. In addition, the orbital phase dependence of the polarization is quite sensitive to the size and composition of particulates in the atmosphere. We are exploring this intriguing new observation method in detail, with a paper in progress (Saar & Seager 2004).

In another unanticipated, but very fruitful development, we have developed and refined theory to predict/explain activity induced by close-in exoplanets on their parent stars (Saar et al. 1994). We have also tentatively detected the weak signal of planet-induced activity in archival X-ray data (Kashyap et al. 2004). We originally proposed the idea of planet-induced activity (Cuntz et al. 1990), suggesting both tidal and magnetic star-planet interactions could be possible. Our initial observational searches (in the chromosphere) turned up no clear signal (Saar & Cuntz 1991), but more recent chromospheric (Shkolnik et al 2003) and X-ray studies (Kashyap et al. 2004) show that a magnetic interaction is present in some systems. An improved theory can explain why HD 179949 shows the strongest signal of several systems studied to date (Saar et al. 1994). Studying and

modeling planet-induced activity should prove to be an important tool for exploring the magnetic fields of exoplanets and the stellar field/wind system in which they live.

In parallel research on stellar magnetic activity supporting this work, we have been investigating correlations between stellar cycle periods P_{cyc} (Saar 2002) and amplitudes A_{cyc} (Saar & Brandenburg 2002) with various stellar properties such as rotation period P_{rot} , convection zone depth, and temperature T_{eff} . In both cases, we find stars separate onto different power-law branches (e.g., $P_{\text{cyc}} \sim P_{\text{rot}}^{a_i}$ with $i=1,2,3$; $A_{\text{cyc}} \sim P_{\text{rot}}^{b_i}$ with $i=1,2$) depending on their average activity level. Stars with multiple P_{cyc} have typically have the two periods or amplitudes on separate branches. The maximum A_{cyc} increases with decreasing T_{eff} , reaching a maximum in the mid-K stars. These results help define the variation timescale and amplitude of plage activity that leads to v_r variation.

Other related studies include exploring magnetic fields in very young, active, disk-less T Tauri stars (Johns-Krull et al. 2004), studying the character and causes of activity in very inactive stars which have minimal v_r jitter (Judge et al. 2004). We found strong evidence for super-equipartition field strengths in T Tauris, and evidence for significant contribution from magnetic heating even in the least active of stars.

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